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HYBRID TCP RENO–VEGAS CONGESTION CONTROL FOR RELIABLE DATA TRANSMISSION IN IOFT-BASED UAV NETWORKS

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Abstract
Under Network-Centric Warfare (NCW) paradigm, low-latency, high reliability and reconfigurable communications is required to facilitate persistent information exchange between geographically dispersed aerial and terrestrial communication nodes. Because of the role of the Unmanned Aerial Vehicles (UAV) that enable the existence of Unmanned Aerial Vehicle assisted communication networks, The Internet of Flying Things (IoFT) system has experience extremely fast-varying network topology where topology can changes very rapidly, there can be an instantaneous network disconnection and wireless channels are in a highly dynamic and random manner. The conventional Transmission Control Protocol (TCP) based congestion control algorithms (CCAs) designed for wired networks fail to be performed adequately under such scenarios. The basic TCP Reno algorithm is a loss based CCA that performs efficiently with packet loss recovery but treats the packet loss occurring on wireless link due to transmission impairments as the cause of congestion and so exhibits unstablie throughout. On the other hand, the TCP Vegas algorithm applies delay based estimation of congestion which leads to the stability in the rate and thus may cause less efficient utilization of bandwidth under highly dynamic environment. In this work, a Hybrid TCP Reno-Vegas congestion control model is proposed, that combines the proactive delay based estimation of TCP Vegas and effective loss recovery of TCP Reno so that to enhance transport-layer communication over IoFT-based UAV network. The proposed model was simulated on network simulator-2 (NS-2) under same mobility model, routing and traffic scenario in the context of Unmanned Aerial Vehicle assisted Mobile Ad Hoc Network (MANET).Performance evaluation was conducted using throughput, congestion stability, packet delivery behavior, and transmission efficiency metrics. Simulation shows the hybrid scheme proposed has the best throughput behavior and the stable transmission over TCP Reno and TCP Vegas. With a hybrid model, an average throughput close to 2.28 Mbps is gained, which exceeds 2.02 Mbps for TCP Reno and 1.78 Mbps for TCP Vegas, and a better congestion window adaptation and bandwidth utilization is achieved. These findings indicate that the proposed Hybrid TCP Reno–Vegas mechanism provides an effective congestion control solution for reliable and delay-sensitive communication in IoFT-enabled NCW environments.

1. Introduction

With fast development of wireless communication technologies, communication infrastructure has undergone a drastic transformation for both military and civilian applications. For the new operational concepts like Network-Centric Warfare (NCW) in recent years, the system is expected to achieve information sharing in real-time, distributed coordination and synchronized decision-making among the networked agents Figure 1. This contributes to enhanced situational awareness, increased operational efficiency by achieving interoperability across wide areas, and enhanced timeliness to conduct operations [1], [2]. Such communication environments depend on the continuous delivery of reliable, high-speed, and uninterrupted data between airborne and ground communication nodes. However, with the rise of Internet of Flying Things (IoFT), a novel mobile network has appeared in which unmanned aerial vehicles (UAVs) act as air-based communication relays and support flexible and resilient communications without being backed by any infrastructure. The UAV based communication network is usually known as flying ad-hoc network (FANET). FANETs have following features: high mobility, rapidly changing topology, intermittent connectivity and multi hop communication. Such characteristics make FANETs suitable for mission-critical applications including military operations, disaster response, and emergency communication systems [1] , [2] without fixed infrastructure support. These UAV-assisted networks, commonly referred to as Flying Ad Hoc Networks (FANETs), are characterized by high mobility, rapidly changing topology, intermittent connectivity, and multi-hop communication capabilities. Such characteristics make FANETs suitable for mission-critical applications including military operations, disaster response, and emergency communication systems [3] , [4] . Conventional Transmission Control Protocol (TCP) variants were originally designed for stable wired networks and therefore often demonstrate performance degradation when deployed in highly dynamic wireless environments [5] . Loss-based congestion control mechanisms such as TCP Reno commonly interpret wireless transmission losses as indicators of network congestion, resulting in unnecessary reduction of transmission rates and throughput degradation [6] . Conversely, delay-based approaches such as TCP Vegas estimate congestion proactively through network delay measurements but may underutilize available

bandwidth under rapidly changing wireless conditions [6] . In light of these trends, adaptive congestion control techniques that provide robust and consistent data communication, enhance network throughput, and increase overall stability are increasingly required for IoFT-based communication [3]- [6].

Although congestion control has been researched for traditional mobile ad hoc and wireless networks, research that studies hybrid congestion control for IoFT-based UAV communication has not been extensive. Most studies separately examine TCP Reno and TCP Vegas, but few are focused on integrating these congestion control mechanisms to leverage the benefits of both loss-based and delay-based congestion control mechanisms in the context of dynamic FANETs. To mitigate these issues, we propose a Hybrid TCP Reno-Vegas congestion control model that exploits the ability of TCP Vegas to estimate congestion proactive manner, along with TCP Reno's packet loss recovery properties to offer higher throughput stability, higher bandwidth efficiency, and greater transport layer reliability for IoFT-assisted Network-Centric Warfare systems.

Figure 1: IoFT Connectivity Architecture in Network-Centric Warfare (NCW)

Contributions of this study are summarized as follows:

1. Evaluation of TCP Reno and TCP Vegas performance under dynamic IoFT-based MANET conditions.
2. Design and implementation of a Hybrid TCP Reno–Vegas congestion control mechanism.
3. Comparative simulation-based analysis using NS-2 under identical mobility and traffic conditions.
4. Assessment of throughput performance, congestion stability, and communication reliability for NCW-oriented IoFT environments.

Research Objectives

The main goal of the study is to develop and assess an adaptive congestion control scheme which can achieve better performance at the transport-layer in dynamic Internet of Flying Things (IoFT)-based environments.

The specific objectives are as follows:

1) To evaluate the transport-layer performance of TCP Reno under dynamic IoFT-based Mobile Ad Hoc Network (MANET) conditions.

2) Investigate the throughput stability, transmission characteristics and congestion control behavior of TCP Vegas in identical simulation conditions. To design and implement a Hybrid TCP Reno–Vegas congestion control mechanism that combines loss-based recovery and delay-based congestion estimation.

3) We will study the performance comparison of the three algorithms such as TCP Reno, TCP Vegas and our proposed Hybrid TCP using NS-2 simulation based on parameters: Throughput, Packet Delivery, Congestion Stability and Bandwidth utilization.

4) How to implement NS-2 for comparison of performance among TCP Reno, TCP Vegas and Proposed Hybrid TCP based on performance criteria: Throughput, Packet Delivery, Stability of Congestion and utilization of Bandwidth?

1.1 Research Questions

RQ1: How does TCP Reno perform under dynamic IoFT communication conditions?

RQ2: Does TCP Vegas provide improved transmission stability compared with TCP Reno?

RQ3: Can a Hybrid TCP Reno–Vegas mechanism improve throughput and congestion stability in IoFT-based UAV networks?

2. Literature Review

The development of transport layer congestion control mechanisms has played a significant role in ensuring reliable communication across different network environments and communication devices. In Internet of Flying Things (IoFT) and Network-Centric Warfare (NCW) environments, congestion control becomes increasingly important due to the highly dynamic characteristics of these networks, including node mobility, fluctuating wireless channel conditions, intermittent connectivity, and multi-hop communication behaviour [7] . Considerable research has been conducted on traditional TCP congestion control mechanisms, wireless TCP adaptations, high-speed TCP variants, delay-based and hybrid congestion control approaches, as well as transport protocols designed specifically for highly mobile airborne and ad hoc networking environments [8] . This section reviews the most relevant studies related to TCP Reno, TCP Vegas, hybrid congestion control mechanisms, and congestion management in UAV-assisted wireless communication networks.

2.1 TCP Congestion Control in UAV-Assisted Wireless Networks

Amponis et al. [9] Introduced and evaluated a new TCP variant specifically designed for UAV-assisted wireless communication networks through comparative simulation analysis. Traditional TCP-congestion control behaviors under severe volatile circumstances in the Flying Ad Hoc Network (FANET) such as mobility, rapid changes of topology and disconnections were examined in the article. The authors found that several traditional TCP versions (like TCP Reno) suffer from severe decrease in the throughput because of the high loss rate and instability of the wireless channels. In addition, it pointed out that congestion control methods sensitive to delay can improve stability, but achieving the use of resources efficiency (bandwidth utilization) is the main problem of communication in the environment of the assist of UAVs. Thus it is evident the requirement of dynamic as well as hybrid congestion control mechanism so as to maintain an equilibrium of throughput performance as well as congestion state for air-borne mobile environment.

2.2 Congestion Control Challenges in Flying Ad Hoc Networks

Khan et al. [10] addressed the congestion control and transport layer performance issues for flying ad hoc networks (FANET) with extreme mobility scenarios. The work deals with the reliable data transmission in airborne networks due to dynamic topology change, mobility of UAVs and dynamic wireless channel conditions. As reported by the authors, usual TCP congestion control mechanisms may cause degradation of throughput and instability of received packets due to lack of sufficient adaptation to frequently changing dynamic topology and dynamic wireless channel conditions.

In order to improve bandwidth utilization and communication stability some ad hoc congestion control schemes with adaptation were developed. The results revealed the necessity for new or hybridized congestion control schemes for FANET and IoFT with extreme mobility.

2.3 TCP Performance in High-Speed Wireless Mobile Networks

Mateo et al. [11] performed analysis on TCP performance in 5G mm Wave mobile communications network under unstable wireless scenarios. The researchers analysed the mobility and wireless channel impact on the performance of TCP throughput and the effectiveness of TCP congestion control strategies for the unstable environment with highly mobility and time-variant channels. The paper suggests that the common used TCP congestion control approaches were found to be failed in an unstable wireless link scenario with mobility and dynamic network condition.

They also concluded that the wireless propagation losses and mobility were the primary causes for significant deviations in the values of throughput, latency, and packet loss rate for the high-speed wireless systems.

They indicated that TCP congestion control should have adaptive proactive behaviour in transport layer for maintaining successful communication in wireless environment.

2.4 Machine Learning based Congestion Control for Highly Dynamic Wireless Networks

In study by Yan et al. [12], intelligent congestion control for a highly dynamic wireless communication environment and their effects on the transport layer performance were discussed. In their work they analysed that the performance of traditional congestion control scheme for the TCP are affected in the environments having high degree of dynamics resulting from mobile node and channel variations. They show that the adaptation to the congestion management algorithm and transport protocol is an effective way of improving the throughput, minimizing the packet loss incurred by congestion and controlling the communication process from instability, especially under mobility conditions. They conclude that intelligent and adaptive congestion management technique is a powerful tool for efficient transport in newer wireless network environments.

These results indicate that adaptive congestion control strategies need to be deployed and encourage us to build an integrated transport-layer mechanism that balances throughput and network stability in IoFT.

Optimization of TCP Congestion Control for Dynamic Wireless Networks

Xu et al. [13] suggested an optimization framework to better improve TCP congestion control performance under dynamic wireless communication conditions. Their research highlighted the drawbacks of traditional TCP implementations under varying conditions (e.g. varying bandwidth, mobility and time-varying channel conditions).

The work revealed that common loss-based TCP congestion control mechanism often react strongly towards wireless losses and consequently degrades network performance, e.g. Decreases the achievable throughput and causes instability in the congestion window size. With this motivation, the authors presented an optimized approach with an adaptive congestion response that works well in these conditions with higher efficiency and less instability. According to their simulation, improved congestion control can reduce unjustified reactions of TCP congestion control algorithm with optimized performance under varying wireless environments, and improve network utilization and reliable transmission. These observations prove that transport-layer adaptive optimization is required to support modern mobile wireless and communication systems with dynamic topology and diverse network conditions.

It can thus be concluded that it is worthwhile to research integrating both delay-based estimation and loss-based recovery as complementary congestion control mechanism in an adaptive transport-layer protocol design.

Transport Layer Enhancement for Adaptive Congestion Control

Transport-Layer Congestion Control Techniques

Zhang et al. [14] evaluated the effectiveness of some of transport layer optimisation schemes which improve the congestion control mechanisms for the next-generation mobile communication context. They examined how existing TCP mechanisms perform when operating in networks with varying network conditions, mobility, and in heterogeneous wireless networks. To tackle this, they developed their own adaptation to transport layer congestion control schemes which adjusted transmission behaviour not just in reaction to loss of packet events, but instead taking into account the received information from the network.

In this paper, our simulations showed an increase in congestion response, the consistency of the throughput, and the overall efficiency in communications in a dynamic network. This means the integration of adaptive decision mechanisms into transport-layer protocol mechanisms can provide significant enhancements for performance of the network, in addition to the mitigation of non-productive congestion responses in mobile ad-hoc wireless settings.

The results we observed corroborate our motivation in designing congestion control schemes that hybridize proactive congestion estimation and packet recovery methods to deal with IoFT and UAV.

Hybrid Congestion Control for Wireless Communication Networks

Li et al. [15] studied various hybrid congestion control mechanisms that use several congestion cues in conjunction to gain the performance at transport-layer in an ad hoc dynamic wireless communication environment. They evaluated the limitations of traditional single criterion based loss-based and delay-based congestion controls individually and suggested a hybrid solution framework that can provide adaptive congestion control under diverse network environments and dynamic conditions. The experiment demonstrated in this paper achieves better throughput, less packet retransmission and greater congestion stability at varied mobilities and traffic environments and claimed hybrid control techniques result in better performance than single criterion methods under dynamic environments. The findings in the paper encourage us to develop such hybrid approaches that combine the advantages of both TCP Reno and TCP Vegas congestion control mechanisms.

2.5 Transport Layer Optimization for IoFT and UAV-Assisted Communication

Alotaibi et al. [15] studied performance issues that the transport-layer is experiencing over the communications of Internet of Flying Things (IoFT). They evaluated various methods for adaptively optimizing the transport-layer performance and established communication reliability at the expense of increased mobility. They found that the standard transport protocols are incapable of guaranteeing the steadiness of communication throughput under rapidly changing topologies of network and sporadic wireless connection and their optimization framework provided improved performance in term of reliable communication, less variance of the delay and higher reactivity of transport-layer in a scenario of communication in the UAV assisted network.

They highlighted the necessity of using an adaptively designed mechanism that controls congestion and provides consistent operations with efficient throughput under dynamic environments.

The current investigation builds on these findings and presents a hybrid version of TCP Reno-Vegas designed specifically for IoFT based mobile ad hoc communication scenarios.

Table 1: *Comparative Analysis of Existing Congestion Control Approaches for IoFT and Wireless Communication Environments*

Ref.	Study	Research Focus	Major Findings	Limitation	Identified Research Gap
[11]	Amponis et al. (2023)	TCP variant evaluation for UAV-assisted wireless communication	Conventional TCP variants suffered throughput degradation under FANET mobility; adaptive approaches improved stability	Limited bandwidth optimization and no integrated congestion strategy	Hybrid congestion mechanisms for IoFT remain underexplored
[12]	Khan et al. (2020)	Congestion control challenges in FANET environments	Dynamic topology and mobility reduced throughput and packet delivery performance	Focused on problem identification rather than protocol enhancement	Lack of adaptive hybrid transport-layer mechanisms
[13]	Mateo et al. (2019)	TCP performance evaluation in 5G mmWave wireless networks	Wireless instability negatively affected throughput and congestion behaviour	No transport-layer optimization proposed	Need for adaptive congestion control in dynamic wireless environments
[14]	Yan et al. (2021)	Machine-learning-assisted congestion control	Intelligent adaptation improved throughput and communication stability	Higher implementation complexity and ML dependency	Lightweight adaptive congestion control remains necessary
[15]	Xu et al. (2022)	Optimization of TCP congestion control	Adaptive congestion response improved throughput and reliability	Did not integrate multiple congestion indicators	Opportunity for combining delay and loss-based mechanisms
[16]	Zhang et al. (2022)	Transport-layer enhancement for wireless communication	Adaptive transmission improved responsiveness and throughput stability	Limited focus on UAV-assisted IoFT environments	Need for transport-layer models tailored for IoFT mobility
[17]	Li et al. (2022)	Hybrid congestion control framework	Combining congestion indicators improved throughput and reduced retransmissions	Not designed specifically for FANET/IoFT communication	Further investigation required for UAV communication scenarios

[18]	Alotaibi et al. (2023)	Transport optimization for IoFT communication	Adaptive optimization improved reliability and reduced delay	Did not investigate TCP Reno–Vegas integration	Hybrid congestion control for IoFT transport remains insufficiently explored

The table above highlights that most research focused on optimisation of congestion control and adaptive transport-layer protocol mechanisms and their performance evaluation under time-varying wireless environment. In comparison, very little effort has been made on congestion control approaches incorporating both the loss-based congestion recovery and delay-based congestion estimation into one TCP framework for IoFT-assisted UAV communication systems. So, most previous research adopted congestion control methods individually and analysed in general wireless environments, not particularly in FANET. As a result, this research aims to establish Hybrid TCP Reno-Vegas congestion control model to achieve greater bandwidth utilization, throughput stability and communication reliability under IoFT-based Network-centric Warfare environments.

3. Reliable Data Transmission in IoFT-based NCW Scenario

In the context of Internet of Flying Things (IoFT)-based Network-Centric Warfare (NCW), Unmanned Aerial Vehicles (UAVs) act as airborne relay nodes which enable multi-hop wireless communication for scattered units of combatants on the battle-field [16] . UAV-supported IoFT networks provide robust support for the rapid information transfer, coordination, and mission operations in a highly fluctuating combat zone [14]. In an IoFT network without any fixed communication facilities and constantly moving UAV nodes, rapid changing topology leads the necessity of adaptive transport and congestion control mechanisms in order to sustain communication stability and effectiveness of data transfer.

In this environment, ground control station and battlefield nodes transmit data among each other via chained UAV relay nodes creating a self-organizing Flying Ad Hoc Network (FANET). Figure 2 visualizes a conceptual IoFT based NCW communication environment. This connectivity demonstrates a set of UAV nodes and ground nodes placed within an Ad Hoc Multi-Hop Wireless Communication Network where chained UAV relay network forms the communication infrastructure of data forwarding with increased reachability and efficient adaptive routing for mobile UAV nodes with ground nodes under the warfare circumstances.

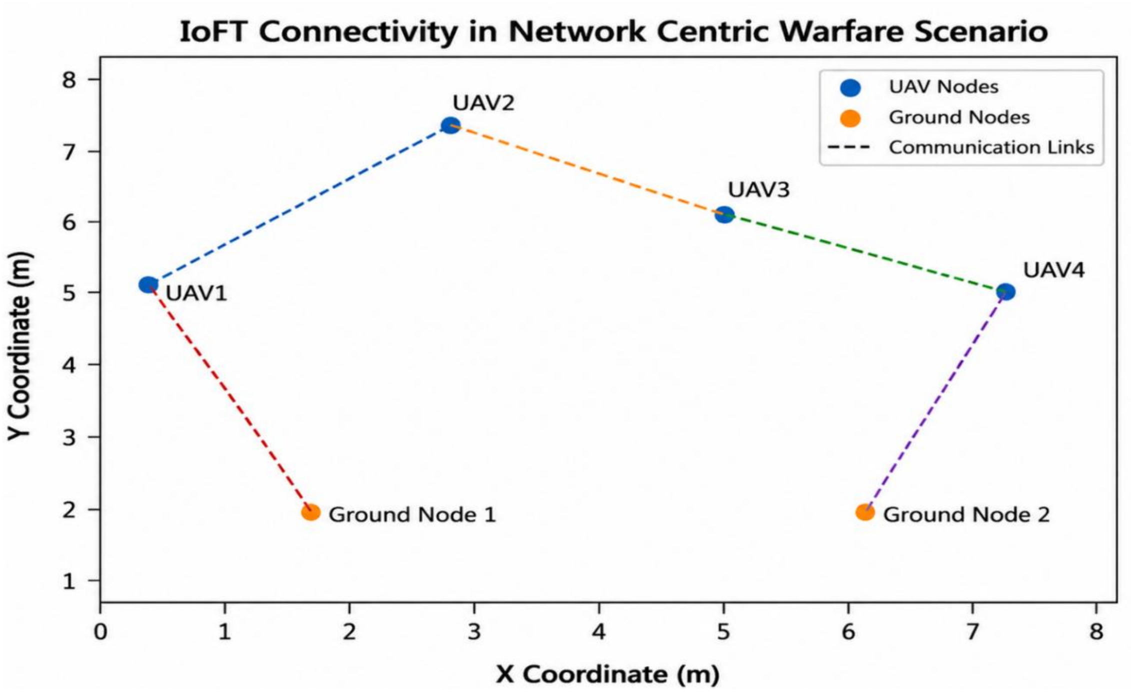

Figure 2: Conceptual Connectivity Architecture of IoFT-Based NCW Scenario

However, Figure 2 shows a high-level view of connectivity among UAVs and other nodes within the framework of an IoFT-based NCW environment whereas, we performed performance evaluation with larger network of UAV nodes under several network scenarios with NS-2.

4. Congestion Control Mechanisms

In order to ensure the reliable communication of transport layer in dynamically Changing IoFT Based NCW environment, the operation characteristics of TCP Reno and TCP Vegas based congestion control methods are discussed as follows in term of how the two methods to detect congestion and to adjust their congestion window sizes.

4.1 TCP Reno Mechanism

TCP Reno is a loss-based congestion control algorithm in which packet loss is used to detect network congestion [21]-[22]. It has 4 phases: Slow Start, Congestion Avoidance, Fast Retransmit, and Fast Recovery. It begins with an exponentially growing congestion window in Slow Start. Once the threshold is reached, it increases linearly. Upon detecting packet loss, TCP Reno performs multiplicative decrease by halving the congestion window, which may lead to throughput degradation in wireless environments where losses are not always due to congestion. The operational phases of TCP Reno congestion control are illustrated in Figure 3

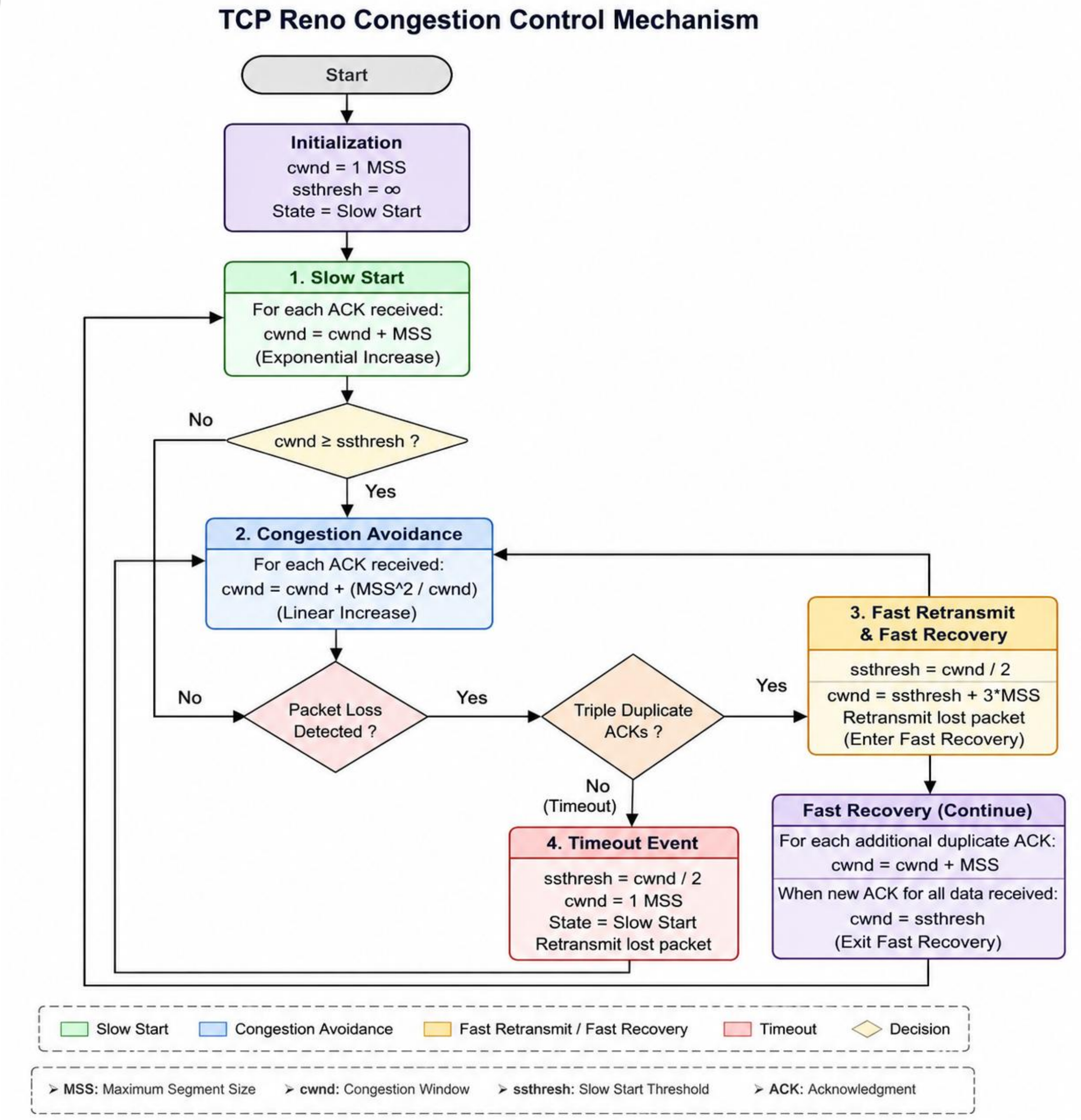

Figure 3: Operational Flow of TCP Reno Congestion Control Mechanism

a) Slow Start:

For the Slow Start phase of TCP Reno, it increases the congestion window exponentially by adding one Maximum Segment Size (MSS) for each acknowledgment (ACK) received to it.

$$cwnd_{new} = cwnd_{old} + MSS$$

where:

- cwnd = Congestion Window Size (bytes or segments)
- MSS = Maximum Segment Size (bytes)
- ACK = Acknowledgment packet

Resultantly, the congestion window approximately doubles during each Round Trip Time (RTT) until its value reaches the defined slow start threshold (ssthresh).

b) Congestion Avoidance:

After reaching the threshold value (ssthresh), TCP Reno enters the Congestion Avoidance phase and increases the congestion window gradually using additive increase

$$cwnd_{new} = cwnd_{old} + \frac{MSS^2}{cwnd}$$

where:

- cwnd = Current congestion window (bytes)
- $MSS^2/cwnd$ = Increment per acknowledgment (bytes/ACK)

This linear increase results in approximately one MSS increase per RTT, allowing the sender to probe available bandwidth while reducing congestion risk.

This scheme adheres to the AIMD (Additive Increase Multiplicative Decrease) principle and is suitable to the resource sharing and fairness management of heterogeneous networks with heterogeneous streams [17].

c) Packet loss detection and handling

TCP Reno executes multiplicative decrease in cases of packet loss, discovered either through a triple duplicate ACK or a timeout event.

i. Slow Start Threshold Update

$$ssthresh = \frac{cwnd}{2}$$

where:

- Ssthresh = slow start threshold (in bytes)
- Cwnd = congestion window (in bytes)

This lowers the threshold value to one-half the data rate now provided.

ii. Congestion Window Reduction

For triple duplicate ACK events:

$$cwnd = ssthresh$$

For timeout events:

$$cwnd = MSS$$

where:

- MSS = Maximum segment size (in bytes)

Three duplicate ACKs signal moderate congestion and can be transmitted by the congestion avoidance mode but an event that exceeds the timeout value implies severe congestion, and the receiver again enters the Slow Start mode.

This multiplicative decay mechanism allows TCP Reno to adapt quickly to situations of congestion while remaining fair and maximizing efficient network usage [18].

4.2 TCP Vegas Mechanism

TCP Vegas is a delay-based congestion control algorithm that improves transport-layer performance through proactive congestion detection using Round Trip Time (RTT) measurements. Unlike TCP Reno, which primarily relies on packet loss as an indication of congestion, TCP Vegas estimates impending congestion before packet losses occur by comparing the expected throughput with the actual throughput of the connection [19] . Depending on the difference between these throughput values, TCP Vegas varies the congestion window (cwnd) to sustain steady state transmission rate, and control packet loss [26]. TCP Vegas has fixed thresholds parameters and , used to evaluate if congestion window should be adjusted up, down or kept constant, thus the congestion window variation is smooth, packet losses, retransmissions and steady state transmission rate have a smaller fluctuation when compared to traditional loss based TCP mechanisms. However, under highly dynamic IoFT and UAV-assisted communication environments, rapid topology changes and fluctuating wireless delays may result in bandwidth underutilization and inaccurate RTT estimation [20]. The operational flow of the TCP Vegas congestion control mechanism is illustrated in Figure 4.

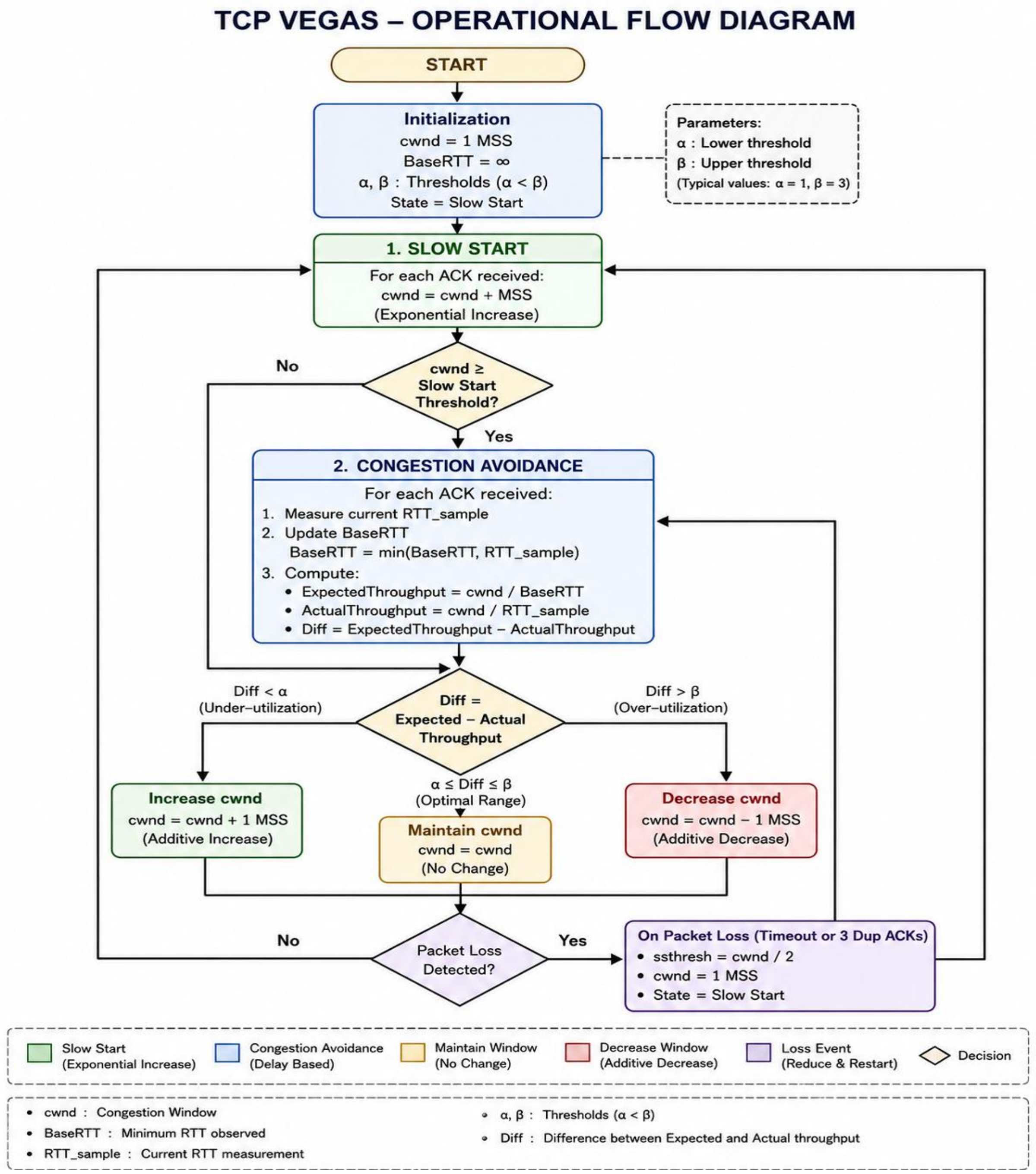

Figure 4: Delay-Based Congestion Control Operation of TCP Vegas

a) Slow Start:

In the Slow Start phase, TCP Vegas initially behaves similarly to previously discussed TCP Reno by increasing the congestion window exponentially driven by received acknowledgment. However, TCP Vegas continuously monitors RTT variations to detect congestion before packet loss occurs [21].

$$Cwnd_{new} = Cwnd \quad + MSS$$

where:

- Cwnd = Congestion Window (bytes or segments)
- MSS = Maximum Segment Size (bytes)
- ACK = Acknowledgment packet

While the above mechanism effectively doubles the congestion window approximately every RTT, the presence of RTT monitoring makes the algorithm to advance to the congestion avoidance region much earlier.

b) Network Congestion Awareness & Congestion Window Management

During congestion avoidance, TCP Vegas estimates congestion by comparing expected throughput with actual throughput [22].

i. *Expected Throughput*

To calculate the expected throughput we use minimum measured RTT:

$$Expected_{rate} = \frac{Cwnd}{BaseRTT}$$

where:

- Expected Rate = Expected transmission throughput (bytes/s)
- cwnd = Congestion Window (bytes)
- BaseRTT = Minimum observed Round Trip Time (ms)

BaseRTT represents the delay under uncongested network conditions.

ii. *Measured throughput*

The actual measured speed is calculate using current RTT value.

$$Actual\ Rate = \frac{cwnd}{RTT}$$

where:

- Actual Rate = Actual throughput in bytes/s
- RTT = Current Round Trip Time (ms)

iii. *Difference Calculation*

TCP Vegas utilizes congestion-window adjustment based on calculating the difference between average rate and average queue growth. In other words, TCP Vegas has made an attempt at using the queuing rate as opposed to just assuming.

$$Diff = Expected\ rate - Actual\ rate$$

where:

- Throughput difference is in bytes per sec

A large value of Diff shows increasing conditions of traffic congestion.

iv. *Rules to Congestion Window Adjustment*

If (is less than) that lower threshold, extra bandwidths are assumed to be available.

Window Increase Condition

$$if\ Diff < \alpha \Rightarrow cwnd = cwnd + 1$$

where:

- α = Congestion threshold (segments) lower

This condition slowly increases the rate of transmission.

If the difference exceeds threshold high (β), there will be Congestion.

Window Decrease Condition

$$Diff > \beta \Rightarrow cwnd = cwnd - 1$$

where:

- β = Congestion threshold (segments) upper

If:

$$\alpha \le Diff \le \beta$$

The congestion window remains unchanged.

Stable Window Condition

$$\alpha \le Diff \le \beta \Rightarrow cwnd = cwnd$$

This delay-based congestion estimation mechanism allows TCP Vegas to maintain smoother throughput behavior and reduce unnecessary retransmissions [23].

c) Packet Loss Handling

Although TCP Vegas primarily relies on delay-based congestion estimation, it incorporates controlled packet recovery to maintain reliable transmission under severe congestion conditions [24].

i. *Slow Start Threshold Update*

The slow start threshold is updated as follows:

$$ssthresh = \frac{cwnd}{2}$$

where:

- ssthresh = Slow Start Threshold (bytes)
- cwnd = Current Congestion Window (bytes)

ii. *Congestion Window Reduction*

Following packet loss detection, the congestion window is reduced to the slow start threshold for packet loss recovery:

$$cwnd = ssthresh$$

For severe timeout events:

$$cwnd = MSS$$

Unlike TCP Reno, TCP Vegas attempts to avoid abrupt transmission reduction by combining proactive congestion estimation with controlled retransmission behavior [25].

4.3 Proposed Hybrid TCP Reno-Vegas Model

The suggested model, a Hybrid TCP Reno-Vegas congestion control mechanism, utilizes congestion estimation, which relies on an application's estimated delay, to cope with the negative effects of packet losses on the network congestion, whilst incorporating packet-loss-based recovery function from TCP Reno, which helps enhance the overall transport performance in highly dynamicIoFTand UAV-based communication scenario. Reno has reliable congestion recovery using the packet loss-based congestion estimation and multiplicative decrease mechanism [33] whereas, the adaptive congestion estimation helps enhance control of congestion window and effective bandwidth utilization during a wide range of heterogeneous wireless channel conditions [34]. Therefore, this hybrid approach attempts to offer throughput robustness, high bandwidth efficiency, decrease in retransmission rate, lower delay between ends, and increased communication quality.

Unlike most other TCP protocols which use loss-only-based approach to control congestion, this hybrid method constantly measures delay and updates estimated congestion with respect to an RTT while retaining Reno's response behaviour under lossy conditions of severe congestion.

The flowchart for the operation of the proposed Hybrid TCP Reno-Vegas congestion control protocol is presented in Figure 5 .

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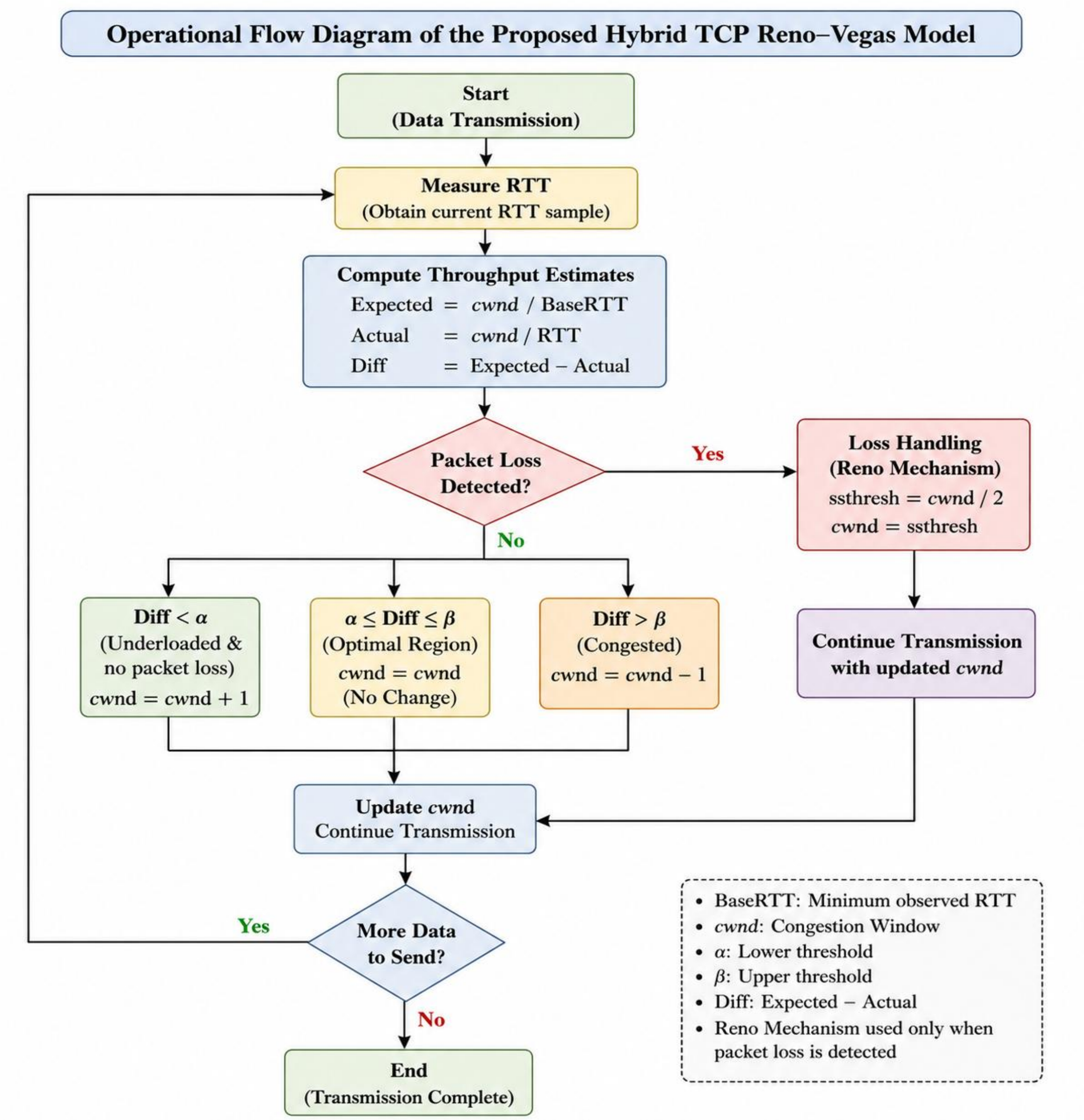


Figure 5: Operational Flow Diagram of the Proposed Hybrid TCP Reno–Vegas Congestion Control Model

Unlike conventional congestion control mechanisms that rely exclusively on either packet loss detection or delay estimation, the proposed Hybrid TCP Reno–Vegas model introduces an integrated transport-layer approach that combines RTT-based proactive congestion estimation with Reno-based packet loss recovery mechanisms. This protocol facilitates the active alteration of congestion window dimensions based on network situation but ensures effective communication even at harsh congested situation. Combination of early congestion detection alongwith controlled congestion recovery, this proposed model is designed to improve stability of throughput, reduction in unnecessary re-transmissions, increase bandwidth utilization, and maintain reliable communication in highly dynamic Internet of Flying Things (IoFT) and UAV-assisted Mobile Ad Hoc Network (MANET) environments.

a) Throughput Estimation (Vegas Component)

The proposed hybrid model first applies proactive congestion estimation by utilizing RTT measurements. [26].

i. Expected Throughput

The estimated available throughput is calculated based on the minimum observed RTT (BaseRTT).

$$Expected = \frac{cwnd}{BaseRTT}$$

where:

- Expected = Expected throughput (bytes/s)
- cwnd = Congestion Window (bytes)
- BaseRTT = Minimum observed Round Trip Time (ms)

ii. Actual Throughput

Actual throughput can be estimated from the current RTT.

$$Actual = \frac{cwnd}{RTT}$$

where:

- Actual = Actual transmission throughput (bytes/s)
- RTT = Current Round Trip Time (ms)

iii. Difference of throughput Calculation

Congestion level estimates may exist.

$$Diff = Expected - Actual$$

where:

- Throughput difference in (bytes/s)

When values of Diff are high, it means more congestion is experienced. The throughput estimation works as depicted in the flow in Figure 5 where RTT is monitored and utilized for traffic monitoring and estimation. [27].

b) Congestion Window Adjustment (Hybrid Control)

In based on the evaluated change in throughput difference(Diff), hybrid model dynamically adjust the congestion window.

i. Window Increase Condition

If additional bandwidth is available:

$$Diff < \alpha \Rightarrow cwnd = cwnd + 1$$

where:

- α = congestion threshold (segments) lower

This is a gradual improvement in transmission capacity.

ii. Window Decrease Condition

If impending congestion is detected:

$$Diff > \beta \Rightarrow cwnd = cwnd - 1$$

where:

- β = congestion threshold (segments) upper

This mechanism stops that excess growth ofcongestion.

iii. Stable window Condition

If congestion remains acceptable:

$$\alpha \le Diff \le \beta \Rightarrow cwnd = cwnd$$

This congestion window remains unchanged.

With this adaptive control a less lumpy and thus smoother throughput behavior as well as more steady state of congestion management could be achieve under the influence of a wireless channel. [28], [29].

c) Handling of packet losses (Reno element)

Upon detection of packet loss through either retransmission timeout or duplicate acknowledgment, the proposed hybrid model enables the TCP Reno recovery process.

i. Slow Start Threshold Update

$$ssthresh = \frac{cwnd}{2}$$

where:

- ssthresh = Slow Start Threshold (bytes)
- cwnd = Current congestion window (bytes)

ii. Congestion Window Reduction

After threshold update:

$$cwnd = ssthresh$$

For severe timeout:

$$cwnd = MSS$$

where:

- MSS = Maximum segment size in bytes

A new Reno, Nevada based recovery function increases resilience for power transmission in conditions of extreme demand, ensuring continued communication [30]- [31].

d) Hybrid Decision Logic

The operation sequence of the algorithm proposed is as following:

1. Measure RTT continuously
2. Compute Expected Throughput
3. Compute Actual Throughput
4. Calculate Diff
5. If Diff < α → Increase cwnd
6. If Diff > β → Reduce cwnd
7. If packet loss → applying Reno-based recovery

e) Summary

In this study, we propose a novel Hybrid TCP Reno-Vegas model that integrates together : Vegas is a proactive delay-based congestion detection scheme and Reno is a resilient packet-loss recovery mechanism By bringing these mechanisms into the scope of a single transport-layer protocol and using their combined features, this model provides stable throughput, lowers down the transmission oscillations, improves the utilization of available bandwidth, and elevates the overall communication performance in IoFT enabled UAV Communication Environments. [9].

5. Research Methodology

This article proposes the performance of an end-to-end Transport Layer Congestion Control with the Help of Communication through Internet of Flying things (IoFT). Simulation based quantitative research method using Network Simulator (NS2 version 2) is utilized to systematically analyze the performance under dynamic network environments. UAV assisted MANET was developed in NS2 to mimic the communication within highly mobile and without infrastructure like environment of NCW, the environment where mobility is of concern.

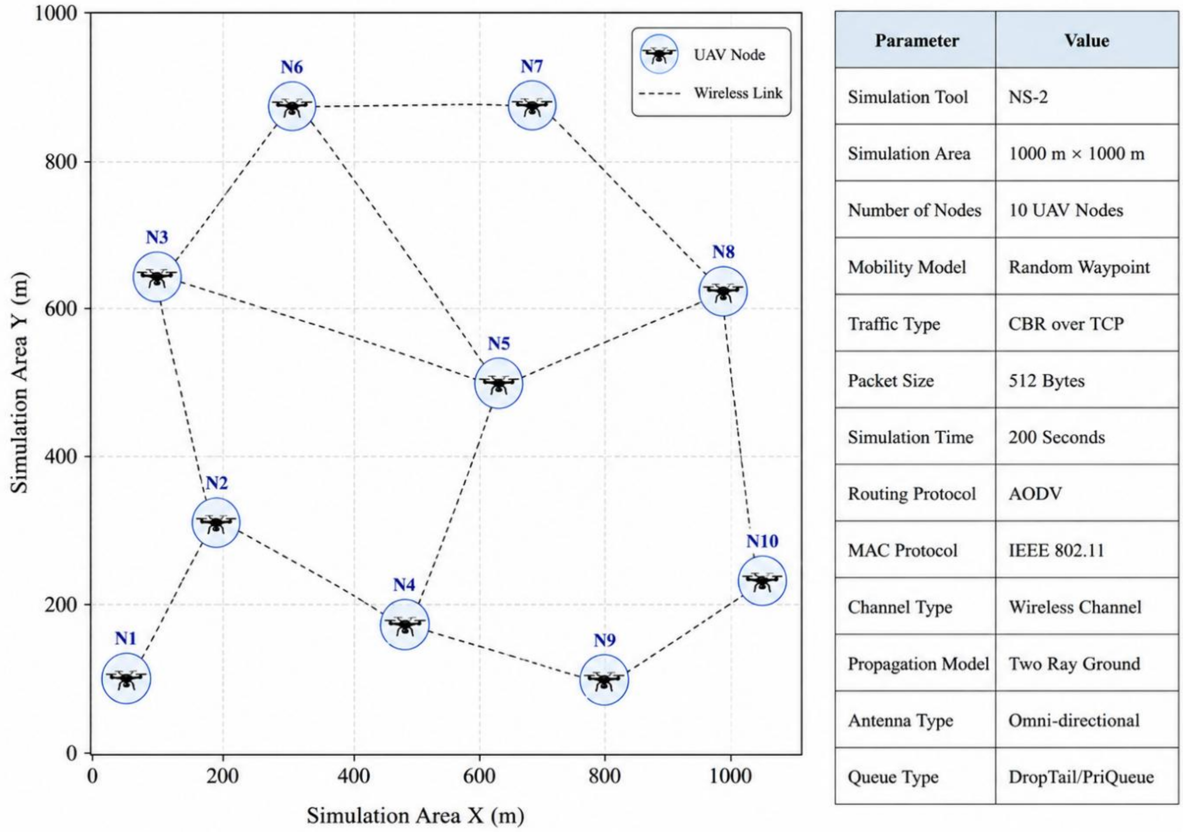
The article tests and evaluates the performance of three congestion controls i.e., TCP Reno, TCP Vegas, and an optimized Congestion Control which is an hybridization of Reno and Vegas (referred as Proposed Model or Hybrid Model TCP reno-Vegas in this paper) as they offer different mechanisms to achieve the optimum flow control at end-to-end.

The simulations are carried out with same number of traffic generators, same level of Mobility and mobility behaviour of vehicles, same path selection in Ad hoc routing along with same transmission parameters for each test. Throughput and congestion stability, efficiency were the key network performance indicators under analysis with the help of NS2 during simulations for a time period of 200 seconds and it's observed the proposed model performed optimally [32].

6. Simulation Scenario and Network Configuration

A simulation setup was prepared using the Network Simulator 2 (NS-2) to perform the comparison of the performance among TCP Reno, TCP Vegas, and the new Hybrid TCP Reno-Vegas. [33] . The simulation environment models the scenario of a UAV-helped Mobile Ad Hoc Network (MANET) in a realistic and volatile wireless communication environment. Number of UAV nodes were created within the simulation region in order to achieve the establishment of multi-hop connection and simulate with real IoFT data transmission based situations.

The simulation topology consists of a set of inter-linked UAV nodes communicating over a wireless medium without any support from the traditional fixed networks. As the topology is dynamically changing due to mobility, the simulation scenario reflects what actually happens in the IoFT and NCW systems supported by UAV. Figure 6 shows NS-2 simulation scenario for performance comparison of protocols along with arrangement of UAV nodes and multi-hop paths.



Parameter	Value
Simulation Tool	NS-2
Simulation Area	1000 m × 1000 m
Number of Nodes	10 UAV Nodes
Mobility Model	Random Waypoint
Traffic Type	CBR over TCP
Packet Size	512 Bytes
Simulation Time	200 Seconds
Routing Protocol	AODV
MAC Protocol	IEEE 802.11
Channel Type	Wireless Channel
Propagation Model	Two Ray Ground
Antenna Type	Omni-directional
Queue Type	DropTail/PriQueue

*Figure 6: NS-2 implementation Simulation of scenario with UAVs (Connectivity Model of 10 nodes)**

**A node represents a UAV and edges correspond to wireless communication links between adjacent UAV nodes. Topologically it shows dynamic multihop routing and wireless links in the simulation setup.*

The main goal of the simulation was the comparison of the congestion control performances of three variations; TCP Reno, TCP Vegas, and Hybrid TCP Reno-Vegas model under dynamic environments. The performances were evaluated in terms of throughput, packet behavior (transmission/arrival), Congestion window variation, End-to-end delay and effective packet loss handling. In all cases the standard Wireless communication and MANET simulation parameters have been used to ensure network stability and real behavior during the performance analysis and comparison all. Table 2 summarizes the network parameters used during the simulation process.

Table 2: *Simulation Parameters for UAV-Based MANET Performance Evaluation*

S. No	Parameter	Value
1.	Simulation Tool	NS-2
2.	Simulation Area	1000m x 1000m
3.	Number of Nodes	10 UAV nodes
4.	Mobility Model	Random Waypoint
5.	Traffic Type	CBR over TCP
6.	Packet Size	512 bytes
7.	Simulation Time	200 seconds

8.	Routing Protocol	AODV
9.	MAC Protocol	IEEE 802.11
10.	Channel Type	Wireless Channel
11.	Propagation Model	Two Ray Ground
12.	Antenna Type	Omni-directional
13.	Queue Type	Drop Tail /Pri-Queue

The Random Waypoint mobility model was utilized to simulate the movement of constant speed UAVs within the coverage area. AODV was utilized to construct dynamically routed paths among the communicating nodes. [34] , [35]. To describe and study behavior of realistic wireless environment, the IEEE 802.11 MAC-protocol and wireless channel models were used to simulation. With this configuration it will be possible to analyze and assess all congestion controls and mobility environments.

7. Data Analysis and Performance Evaluation

In this part, we introduce the performance simulation carried for different congestion control mechanism; which include TCP Reno, TCP Vegas, and the introduced Hybrid congestion control mechanism-Hybrid congestion control model TCP Reno-Vegas in mobile ad-hoc network using internet of flying things (IoFT) basis communication. In terms of evaluating this hybrid model, the capability of controlling congesting issues over IoFT based mobile ad hoc networks are checked and proved whether this mechanism can successfully run in a fast changing (topology and trafic) environment, and provide high and efficient end-to-end communication protocol to achieve stable throughput performance, reliable communication, efficient transmission and effective congestion handling mechanism. Unlike other congestion control mechanisms that respond to network packet loss or packet delay only (one parameter to response), this proposed hybrid method (Hybrid congestion control model TCP Reno-Vegas) in terms of responding to both the factors- packet loss & packet delay.

In Network-Centric Warfare (NCW) IoFT, continuous and real time communication between all the participating nodes (flying things, stations) are needed; therefore transport layer mechanism must preserve all the packets transmitted (retransmissions and good retransmissions), also reduce maximum delay and maintain its throughput under different network conditions for efficient operation of the system.

Here, we perform a comparative study of our proposed algorithm with existing one including best one, to investigate throughput, stability and congestion features.

7.1 Throughput Performance Analysis

The throughput performance has been evaluated to analyze the efficiency of TCP Reno, TCP Vegas and Hybrid TCP Reno-Vegas model. To have continuous flow of data over IoFT-based ad-hoc wireless network with different changing of node position(mobility). The throughput of Each protocol has measured for each unit time intervals through-out simulation.

(a) TCP Reno Throughput Analysis

TCP Reno exhibits noticeable throughput fluctuations throughout the simulation interval. The throughput initially increases as network resources become available but experiences periodic reductions during congestion events as illustrated in Figure 7.

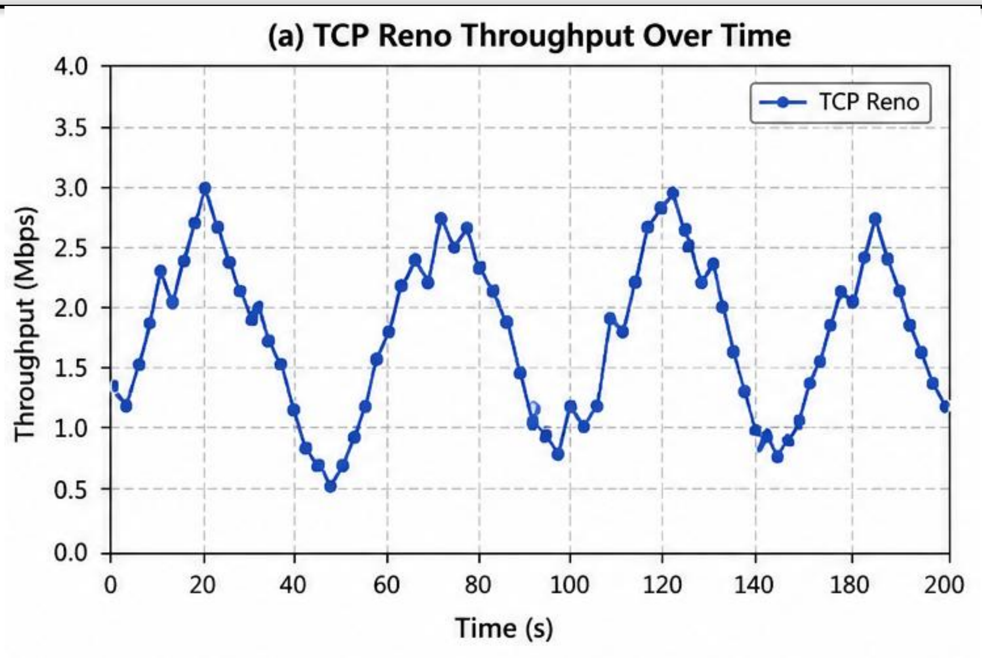


Figure 7: Throughput Performance of TCP Reno

This is because of the loss-based congestion control method adopted by TCP Reno where the occurrence of packet loss signals network congestion and thus throughput goes up and down because of congestion window being increase and decrease. Throughput has been varied in the simulation from roughly 0.5Mbps to 3Mbps and the average throughput is around 2.02 Mbps. Reno obtained short-term throughput peaks but is hard to keep throughput constant when networks are changing dynamically.

(b) TCP Vegas Throughput Analysis

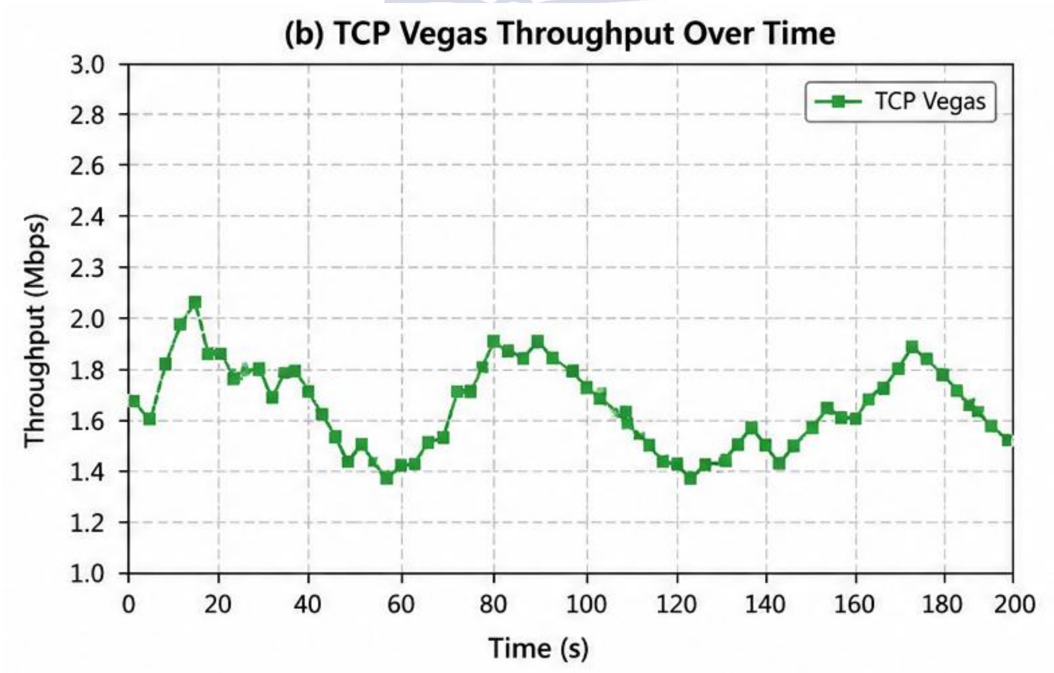


Figure 8: Throughput Performance of TCP Vegas

Figure 8 shows the throughput performance of TCP Vegas. Compared to Reno the throughput seems to be smoother and under better control over the time of simulation. The underlying concept is delay based congestion detection by the TCP Vegas which can detect congestion even before packets are lost thus helping in preventing from sharply losing the throughput values. However the values of the throughput are seen to stay in a tight range between around 1.3-2.2 mbps with an average throughput value of about 1.78 mbps, it can be concluded that due to the more conservative transmission nature the higher values of the throughput cannot be reached by TCP Vegas.

(c) Hybrid TCP Throughput Analysis

The throughput response of Hybrid TCP shown in Figure 9 demonstrates improved performance compared with both TCP Reno and TCP Vegas. The throughput remains comparatively stable while maintaining higher transmission efficiency throughout the simulation duration.

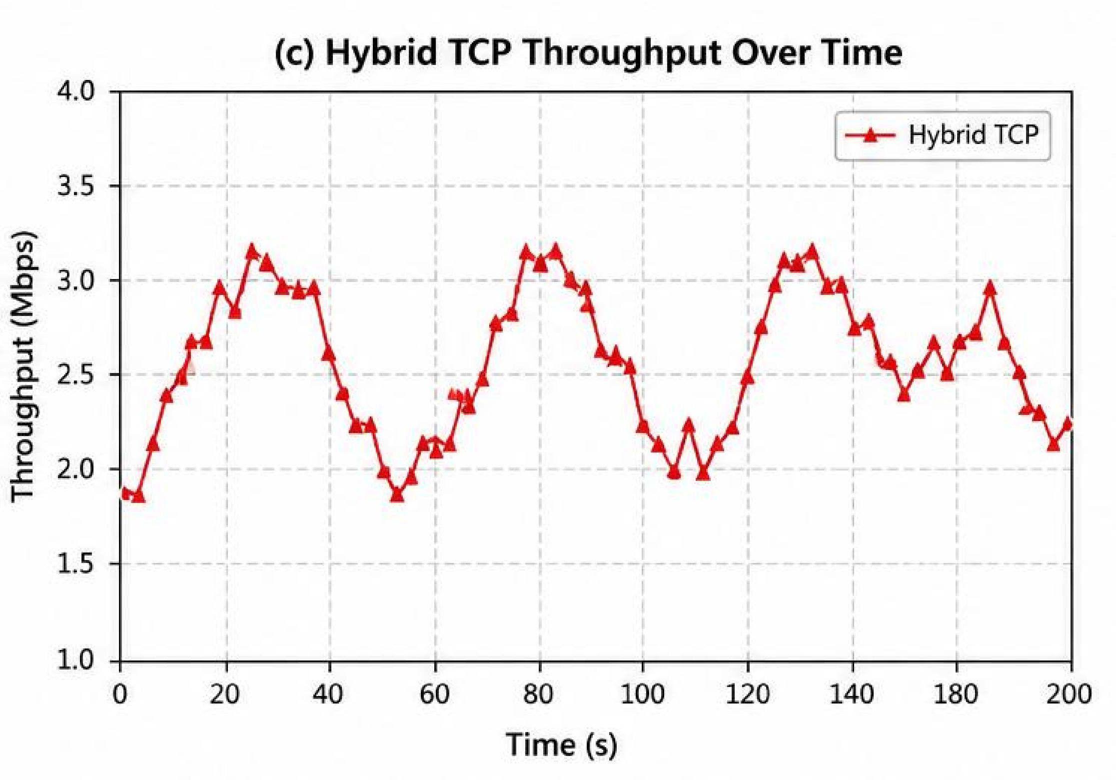


Figure 9: Throughput Performance of Proposed Hybrid TCP Reno–Vegas Model

The hybrid protocol of TCP combines the behaviors of loss-based congestion control protocol and delay-based one, making it be more suitable to respond to the conditions under different network situations, thus leading to good bandwidth utilization and less performance loss under congestion. The observed throughput results ranging from 1.6 Mbps to 3.1 Mbps, with an average throughput of around 2.28 Mbps, being highest of all protocols tested.

(d) Comparative Throughput Evaluation

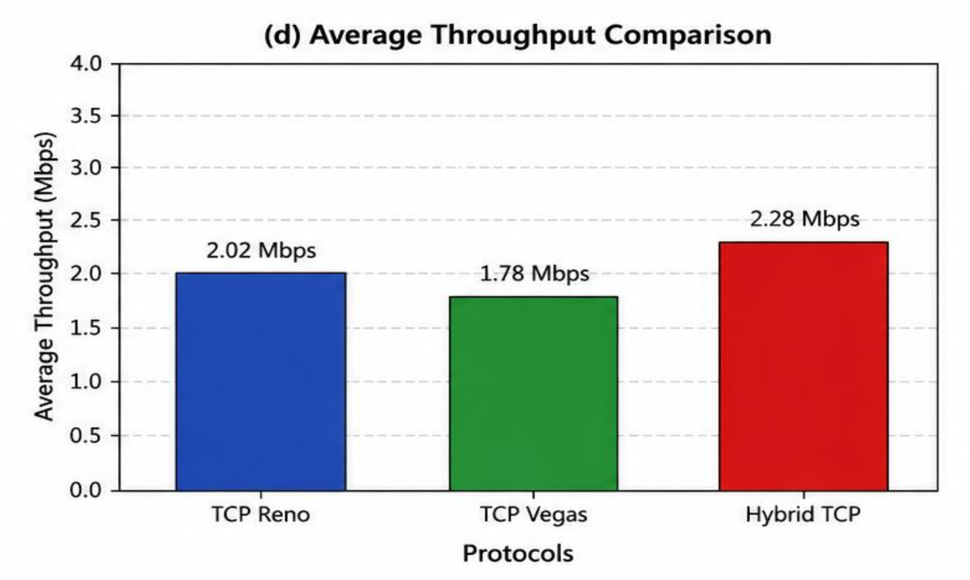


Figure 10: Comparative Average Throughput Performance

Figure 10 represents the average throughput obtained by all of the protocols considered in this work. In terms of comparison between different schemes the Hybrid TCP Reno-Vegas presents higher average throughput, i.e., 2.28 Mbps compared to 2.02 Mbps and 1.78 Mbps of the TCP Reno and TCP Vegas, respectively. The increase is about 12.9% over TCP Reno and about 28.1% over TCP Vegas.

The obtained results reveal that coupling active delay estimation of congestion with robust recovery of packets losses leads to better usage of bandwidth and continuous data transfer under the dynamic environment in IoFT based environment.

All, in all Hybrid TCP show a superior bandwidth utility and continuous transmission which proves that this scheme is performing well in simulated network environment.

7.2 Packet Delivery and Packet Drop Analysis

Analysis of Packet Delivery and Packet Drop The analysis was performed for packet delivery and packet drop on three TCP algorithms (TCP Reno, TCP Vegas and Hybrid TCP Reno-Vegas model) for evaluating the efficiency of proposed Hybrid model, the reliability and congestion handling of all three models on the ad-hoc based mobile networks that are integrated into IoFT. PDR is defined as ratio of delivered packets to the source packets, while packet drop denotes lost packet, because of buffer overflow, congestions, route variations and link instability. Packet Delivery Ratio (PDR) We calculate PDR to investigate the reliable and successful packet transmissions between the source and destination using three TCP algorithms (TCP Reno, TCP Vegas and the Hybrid TCP Reno-Vegas). The Packet Delivery Ratio(PDR) can be expressed as below.

$$\boldsymbol{PDR}\ (\%) = \frac{\boldsymbol{Packets\ Received}}{\boldsymbol{Packets\ Sent}} \times \mathbf{100}$$

where:

- Packets Received = Total packets successfully delivered (packets)
- Packets Sent = Total packets transmitted (packets)
- PDR = Packet Delivery Ratio (%)

Higher PDR values indicate improved communication reliability and transmission efficiency.

- **Packet Drop Percentage**

Packet Drop Percentage was used to measure transmission losses occurring during communication due to congestion, mobility, wireless interference, or routing instability.

$$Packet\ Drop(\%) = \frac{Packets\ Sent - Packets\ Received}{Packets\ Sent} \times 100$$

where:

- Packets Received = Successfully received packets (packets)
- Packets Sent = Total transmitted packets (packets)
- Packet Drop = Packet loss percentage (%)

Lower packet drop values indicate better congestion management and improved transport-layer reliability.

Reliable communication in IoFT-assisted environments requires maintaining high packet delivery while minimizing unnecessary packet loss because communication interruptions may affect network responsiveness and information exchange. Therefore, comparative analysis was performed to determine how efficiently each protocol preserves successful packet transmission under dynamic network conditions.

(a) TCP Reno Packet Delivery Analysis

In the whole simulation period, the packet delivery performance of TCP Reno has the moderate level. Packets were sent in a relatively constant manner but in the congestion and retransmission episodes, packets delivery decreased. Because TCP Reno solely based the transmission rate congestion indication upon packet loss, when congestion happens, it reduces the congestion window size leading to the retransmit delay and likely packet loss increases.

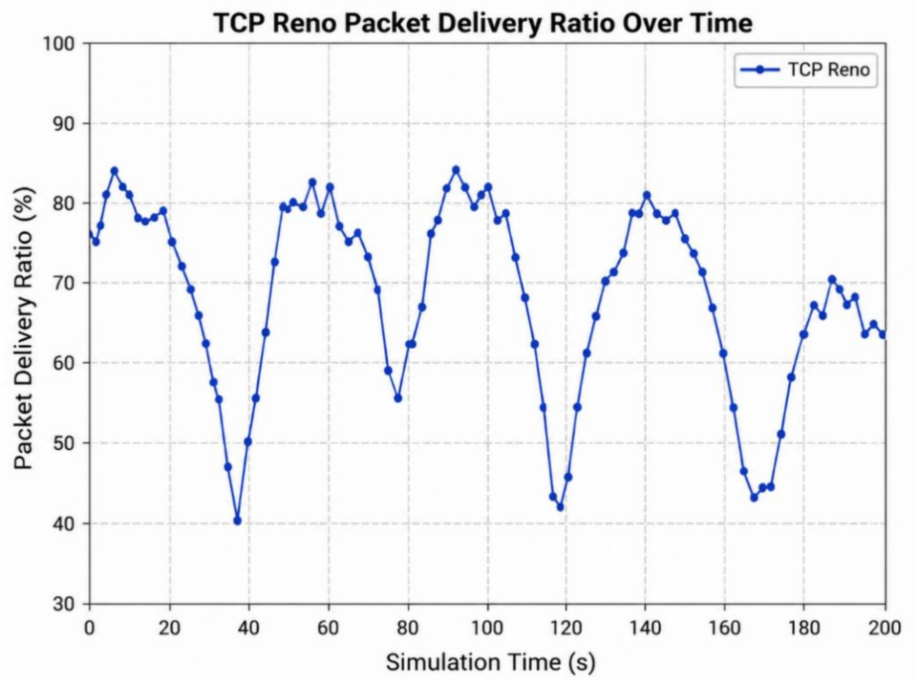


Figure 11: TCP-Reno Packet Delivery Ratio Over Time

From Figure 11, the simulation outcomes show that TCP Reno gains satisfactory packet performance, yet its variation scope of packet loss seems to be a little too wide.

(b) TCP Vegas Packet Delivery Analysis

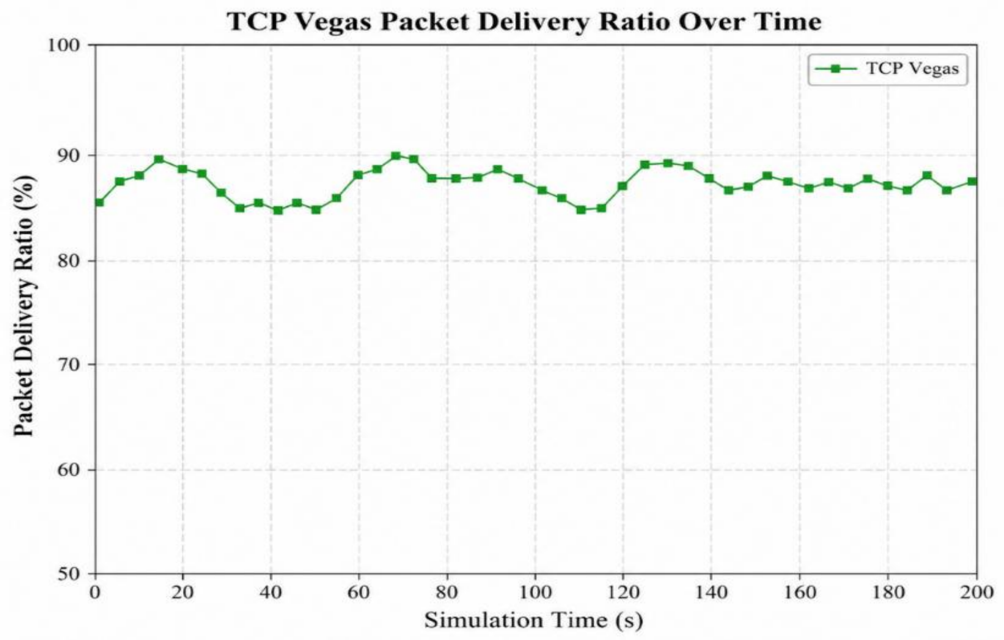


Figure 12: TCP Vegas Packet Delivery Ratio over Time

Above show the packet delivery performance of TCP Vegas. Compared with Reno, packet delivery remains comparatively more stable throughout the simulation. TCP Vegas estimates congestion using delay measurements and adjusts transmission rates before severe packet loss occurs. As a result, fewer packets are dropped and overall delivery consistency improves.

The results demonstrate improved reliability; however, the conservative transmission behavior slightly limits transmission aggressiveness.

(c) Hybrid TCP Packet Delivery Analysis

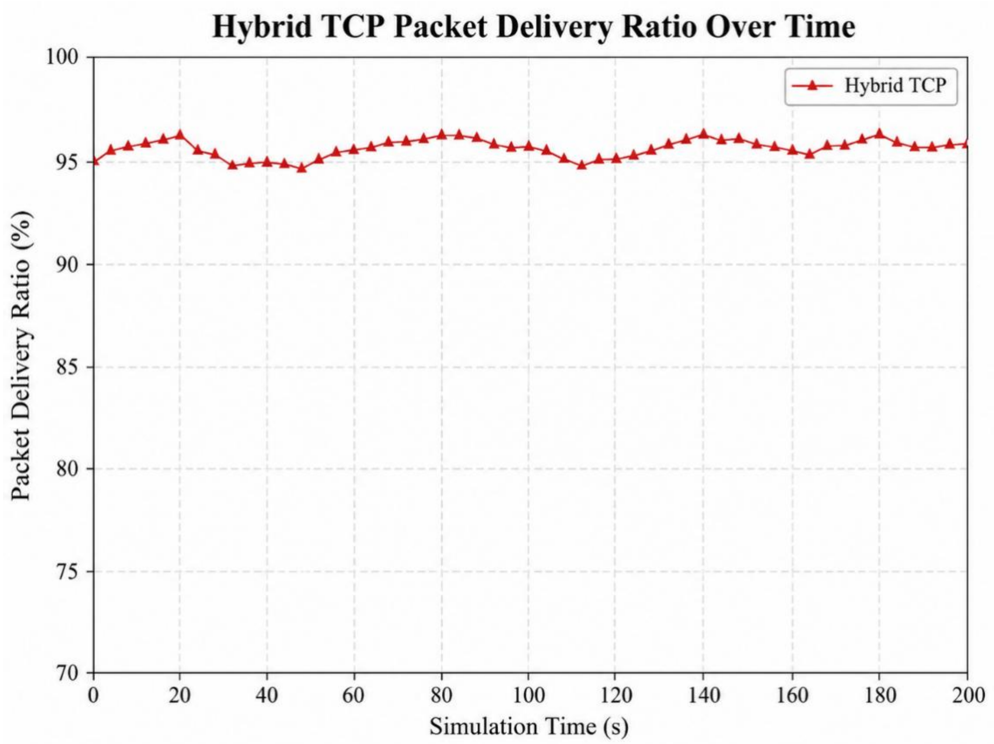


Figure 13: Hybrid TCP Packet Delivery Ratio Over Time

In this figure, it is clear that the success packet transmission rate achieved for Hybrid TCP has consistently improved over Reno and Vegas, because this approach takes advantages of both the loss and delay for network condition detection thus can reduce useless packet retransmissions.

In general, observation made in the simulation also gives evidence for the enhancement of seamlessness and packet preservation.

(d) Average Packet Drop Comparison

Average packet drop percentage observed in the simulation period for TCP Reno, TCP Vegas, and the proposed Hybrid TCP model is shown in Figure 14 . Transport Layer performance is validated by Packet drop ratio as it is an important performance indicator, because the excessive packet loss reduces overall communication reliability, increases re-transmission overhead, and negatively impacts network efficiency.

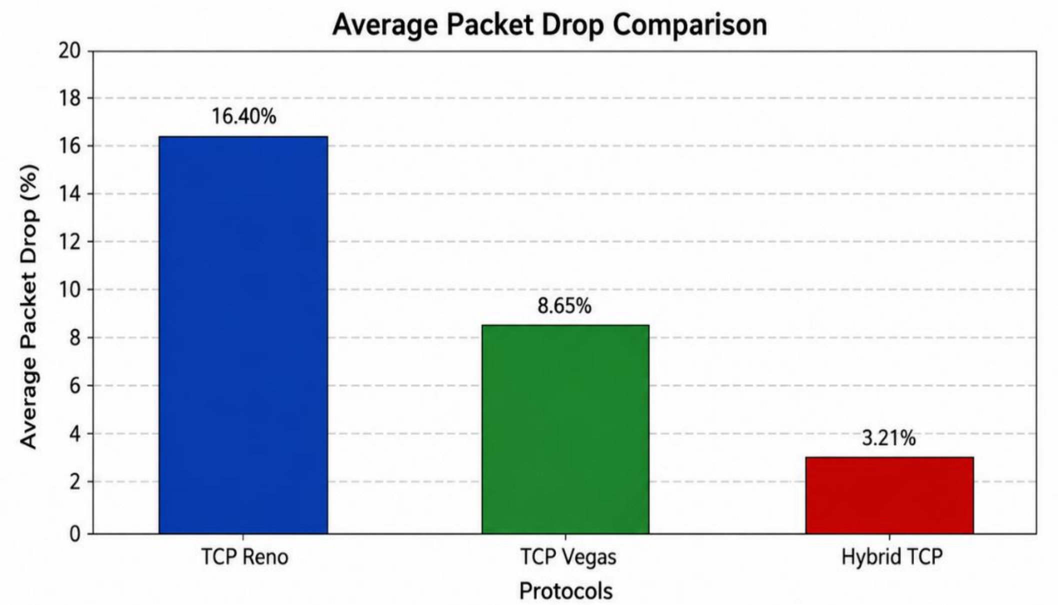


Figure 14: Comparison table of TCP Reno, TCP Vegas, and TCP Hybrid Average Packet Drop

As far as the performance of these protocols is concerned, the simulation shows that TCP Reno achieved packet drop rate approximately 16.40%. The reason for this performance of Reno is that Reno is a loss-based congestion control technique, it is only aware of congestion when packet losses happen and reacts accordingly. When the amount of traffic becomes too high, its slow reaction for the congestion would cause the packet retransmission and packet losses.

On the contrary, the average packet loss of TCP Vegas was about 8.65%. Vegas has a congestion control that is based on packet delay, so Vegas has been capable to detect the congestion in an earlier time and reacts more quickly in order to prevent the packet losses. When it is comes to the average packet drop rate of Hybrid TCP model, it is the smallest which was 3.21% as we compare with Reno and Vegas. Hybrid TCP adopted both delay-based and loss-based congestion control behaviour and was thus able to get better communication performance in the sense of transmission efficiency under those conditions. In conclusion, the study proves that the proposed Hybrid TCP model offers better reliability, efficiency of data transfer and therefore may be suitable for the IoFT-based mobile ad hoc networks communication with high delay and volatility conditions as NCW.

7.3 Throughput Stability Analysis

Throughput stability analysis was conducted to evaluate the consistency of data transmission performance for TCP Reno, TCP Vegas, and the proposed Hybrid TCP model throughout the simulation period. Instead of computing throughput averages across a period of time for all users, the concern in this study of stability is of variation and oscillation in throughput over time. For IoFT-based mobile ad hoc communication, this concern has significance since, network topology and channel conditions dynamically changing frequently in mobile ad hoc network, which might lead to signal dropping for communication. The more the throughput will vary/ oscillate, more and more frequent communication breaks would be incurred.

(a) Throughput Stability Comparison

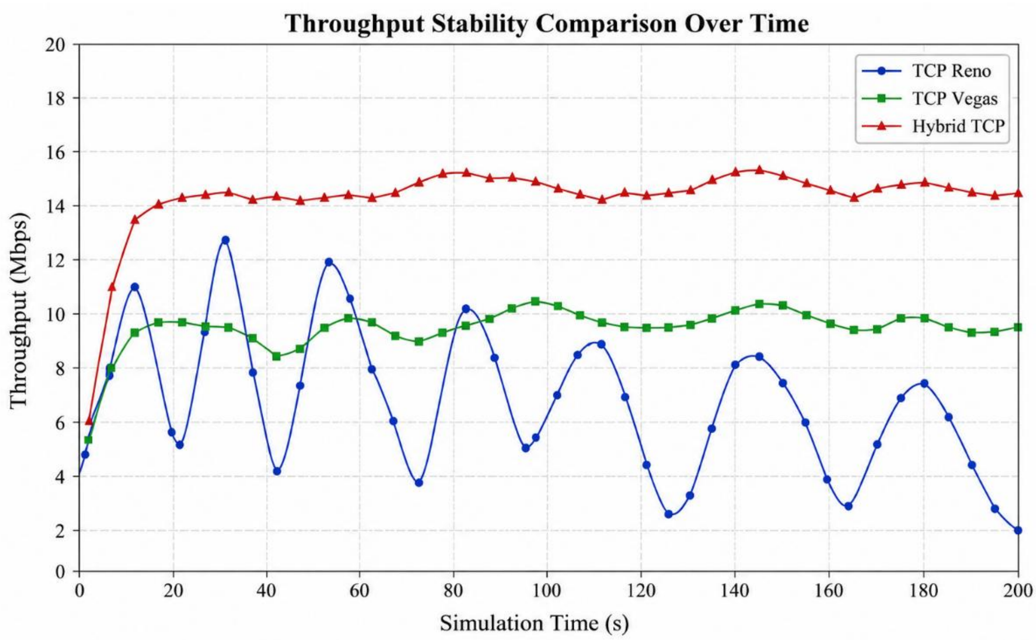


Figure 15: Time-series throughput stability comparison of TCP Reno, TCP Vegas and Hybrid TCP

Figure 15: time series of throughput comparison of TCP Reno, TCP Vegas and Hybrid TCP From the experiment, it can be observed that TCP Reno has the largest fluctuation in the throughput responses with frequent up and down trend owing to rapid and aggressive control on congestion window after packet loss happens. The transmission in TCP Vegas shows smoother trend for its stable throughput due to delay-based estimation, which restricts aggressiveness of transmission. The proposed Hybrid TCP can provide smooth throughput responses and keep higher transmission performance compared with previous solutions due to the relatively small variation on the amplitude of throughput.

(b) Throughput Oscillation Comparison

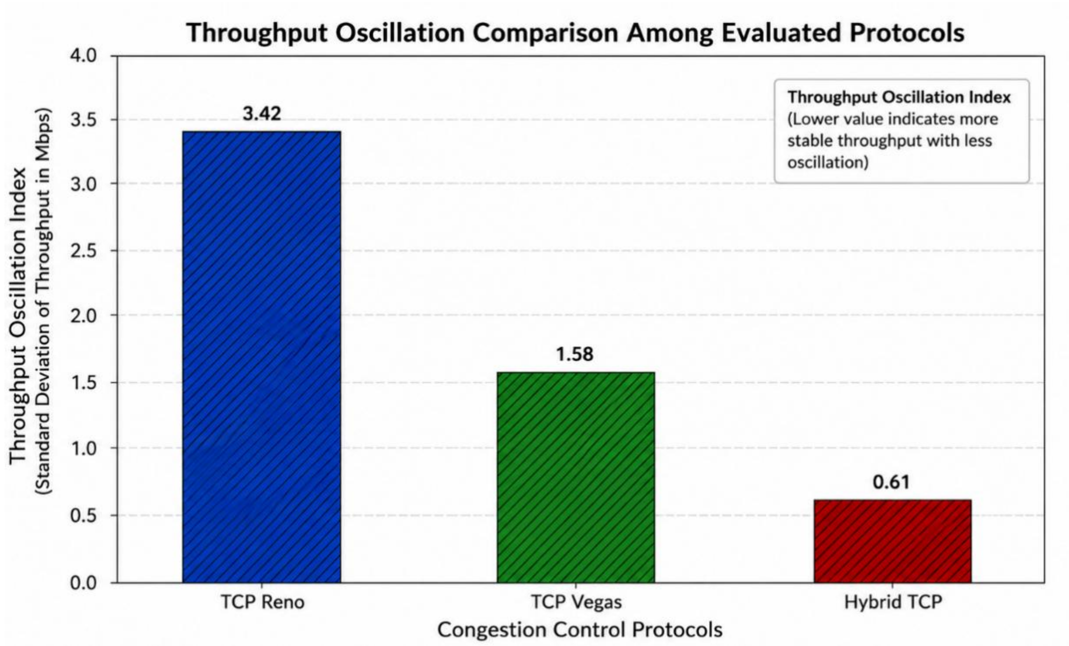


Figure 16: Throughput oscillation comparison among evaluated congestion control protocols

Figure 16 summarizes throughput oscillation among the evaluated protocols. The comparison demonstrates that TCP Reno records the largest throughput variation, indicating unstable bandwidth utilization. TCP Vegas eliminates congestion oscillation but trades this for achievable TCP throughput. The level of oscillation for TCP Hybrid can be seen as having the lowest of all considered congestion methods, yet throughput can be as high as of TCP Reno. This implies that Hybrid TCP response towards congestion leads to better transport level reliability. As shown by the results Hybrid TCP proves optimal in achieving more stable and continuous communication for dynamic IoFT enabled networks.

7.4 Congestion Window Behavior Analysis

Analysis of Congestion Window was applied for the three algorithms - TCP Reno, TCP Vegas, and the novel Hybrid TCP model to measure and manage the actual rate to adapt it based on the different condition of network. Efficient congestion window handling is the main purpose to effectively increase the utilization of bandwidth for sending and to eliminate the retransmission of useless packets.

a) Development Of Congestion Window When Through time

Figure 17 illustrates the variation of congestion window over the period of time. Since congestion management strategy of TCP Reno is loss-based the window tends to increase with frequent drops, therefore it creates non-steady pattern of transmission. In contrast TCP Vegas follows more smooth increase and decrease in the window by employing the mechanism of delay-based estimation but it has the tendency to work more conservatively.

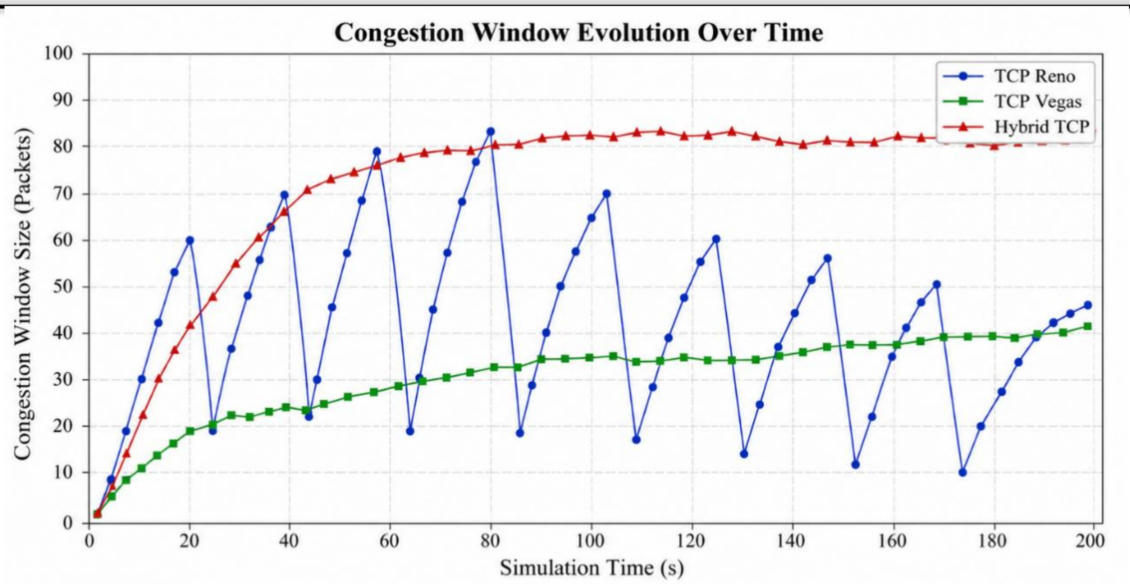


Figure 17: Dynamic of congention window (CWND) over time for TCP Reno, TCP Vegas and Hybrid TCP in … Simulation

The congestion window evolution of Hybrid TCP compared to CC based schemes proves its stable property. The results indicate improved congestion adaptation and more efficient utilization of available network resources.

(a) Average Congestion Window Comparison

Figure 18 presents the average congestion window achieved by each protocol.

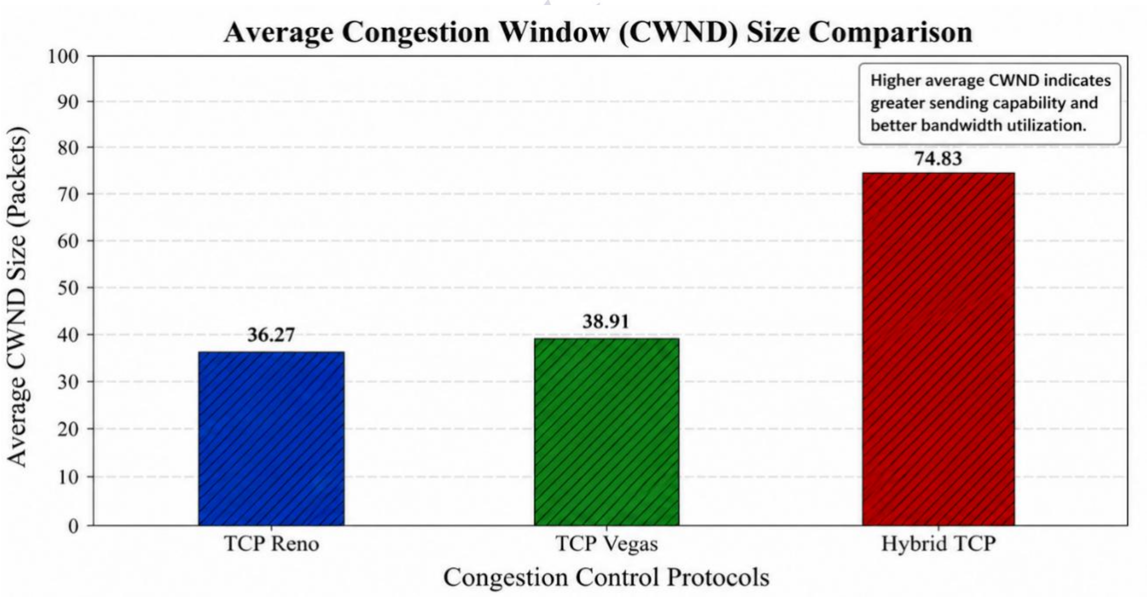


Figure 18: Average congestion window (CWND) size comparison among evaluated protocols

Comparing with Reno and Vegas TCP protocols, Hybrid TCP has the largest average value of CWND, which suggests more effective use of bandwidth and better continuity of transmission. Reno gets the moderate average value of CWND, but larger value of variation, whereas Vegas obtains good control of window size, which is steady but more conservative. Overall, the congestion control and transport-layer performance of Hybrid TCP is better than Reno and Vegas TCP protocols.

7.5 Overall Performance Findings

Overview The overall results gathered from simulation-based assessment on the proposed Hybrid TCP Reno-Vegas model in comparison with TCP Reno and TCP Vegas for IoFT-based mobile ad hoc communication relevant to Network-Centric Warfare (NCW) communications requirements are summarized below. From throughput analysis, the proposed Hybrid TCP presented better performance by providing a larger average throughput along with more persistent transmission as compared to both TCP Reno and TCP Vegas. It could be seen that TCP Reno offered higher but transient peaks in throughput whereas TCP Vegas exhibited a smoother throughput in an average but could not efficiently utilize available bandwidth.

Packet delivery and drop analysis reflected that Hybrid TCP offers enhanced reliability in communications through avoiding extra packets drop in network, and by preserving transmitted packets under different network dynamics.

Furthermore, the throughput stability of Hybrid TCP reveals much less oscillations and smooth data delivery than others whereas congestion window analysis shows more responsive mechanism in data delivery. In NCW context, this gain could be relevant since the overall mission performance heavily relies on continuous information flow among the networked aerial and ground-based systems, seamless and on-time awareness and coordination. Missing link because of transmission lateness and uncertain throughputs make operations difficult for the systems in NCW missions. From this aspect of view, experimental simulation result show Hybrid TCP controls congestion much better than and takes advantage of network available bandwidth much efficient than traditional transport protocol in NCW connection.

8. Advantages of the Proposed Hybrid TCP Reno–Vegas Model

Hybrid TCP Reno-Vegas approach The proposed Hybrid TCP Reno-Vegas model combines the delay-based congestion estimation approach along with loss-based recovery strategy to make the protocol better adaptable at the transport layer under varying channel conditions of a given IoFT or UAV assisted network scenario. Traditional approaches which solely focus on the level of particular loss or delay to estimate congestion only enable limited performance.

On the other hand, the model proposed here provides the advantage of active congestion recognition as well as robust recovery for effective transport layer operation under such dynamically changing channel environments.

a) Adaptive Congestion Awareness

The present approach continually monitor change in round trip time (RTT), that provide measure for estimating the congestion level prior to the packet loss. We exploit our prior congestion estimation for responding earliest to the congestion, preventing the reactive congestion measures. [36].

b) Guaranteed Recovery Against Packet Drop

When significant congestion conditions are identified (via either repeated ACKs or retransmission timeout events), the model switches over to the use of TCP Reno-like recovery mechanisms to avoid losing connectivity altogether [37].

c) Balanced Transmission Control

By adding delay-aware estimation to the controlled congestion recovery, our approach allows a more fair congestion window control and mitigates excessive adjustments of transmit rate which are typical in conventional approaches [38].

d) Resilience in Dynamic IoFT Ecosystems

Proposed model aims to run efficiently under a condition in environment which is associated with :

- High node mobility,
- Dynamic network topology changes,
- Intermittent wireless connectivity, and
- Fluctuating wireless channel conditions.

Such features highlight a beneficial aspect of a model that's desirable to adopt forIoFT supported and UAV empowered mobile systems.

e) Tighter congestion window control

The offered architecture makes more gradual adjustments of the congestion window due to integration of estimates for congestion as well as responsive retransmissions with a certain measure of control. This allows more stable and uniform behavior of transport layer in varying network conditions. [39].

9. Conclusion

The IoFT-based Mobile Ad Hoc Networks (MANETs) faces challenging transport-layer communication due to several factors such as rapid mobility of nodes, fluctuating wireless channels, intermittence connectivity, and frequently changing network topologies. Conventional TCP congestion control algorithms primarily established in relatively stablewiredcommunicationnetworks usually incur poor transport-layer performance in dynamically changing wired environments. This paper addresses the aforementioned issue by proposing a Hybrid TCP Reno-Vegas congestion control mechanism that combines early congestion control of TCP Vegas with the packet loss recovery of TCP Reno.

The proposed model was then designed and simulated under the same mobility, packet generation and routing policy of the IoFT-based UAV-assisted communication system by using NS-2 simulator.

According to the simulation results, it is proved that the proposed Hybrid TCP model outperforms traditional TCP Reno and TCP Vegas methods in transport layer performance. Specifically, the proposed model gained an average throughput of 2.28 Mbps which has improved around 12.9% over the TCP Reno and 28.1% over the TCP Vegas, while smoothly adapting its congestion window and lowering the transmit fluctuation under dynamically wireless environments. The proactive congestion identification and controlled congestion recovery methods integrated in the proposed Hybrid model result in better bandwidth utilization and continuous communications under challenging wireless circumstances. The results conclude that the proposed Hybrid TCP Reno-Vegas model represents a potential congestion control mechanism for the delay-sensitive and throughput-centric network-centric Warfare (NCW) communication as well as a potential tool to enhance communications reliability in IoFT-based UAV communications.

10. Future Work

Even though the proposed hybrid TCP Reno-Vegas has provided enhanced throughput and reliability performance over the proposed scheme in simulated IoFT communication environment, the real-world viability and scalability of the proposed mechanism still needs to be evaluated.
• The initial and major step to validate the proposed scheme would be to implement it in actual UAVs communications with SDR testbed to evaluate the communication performance in real-world mobility, interference and wireless propagation phenomena. • Secondly, further analysis need to be conducted by compared to the advanced congestion control algorithms such as TCP Cubic, and TCP BBR so to verify the performance competitiveness and versatility in the upcoming wireless network conditions.

• Third, Machine learning-based adaptive congestion control can be proposed to optimize the values of the congestion thresholds automatically by learning the dynamically changing traffic, so as to further improve the control decisions and the responsiveness in highly dynamic IoFT environment.

• Performance analysis under different node densities, speed of mobility, intensity of traffic and the various wireless channel environments can also be undertaken to study the scalability and reliability. • In addition, security-based congestion control can be introduced into the Hybrid TCPreno-Vegas in order to withstand various kinds of attack and environmental uncertainties in military NCW applications.

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